

Responses to DEQ Questions

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- 1. Should the current dissolved oxygen criteria (5 ppm daily average and 4 ppm minimum) apply at all depths of a lake or only to the epilimnion of a stratified lake or reservoir or to a depth of 1 m (or 2x Secchi depth) during non-stratified conditions?**

To the committee's knowledge, the United States Environmental Protection Agency (EPA) has not issued specific guidance on how states should apply the existing dissolved oxygen (DO) criteria to lakes and reservoirs. Therefore, states can interpret and apply the DO criteria for stratified water bodies as appropriate. In the absence of direction from EPA, states such as Maryland (MDE, 2004), Minnesota (MPCA, 2003), Oregon (ODEQ, 2003), and West Virginia (WV EQB, 2004) do not currently address the effects of stratification on DO concentrations in their water quality regulations. Alternatively, Colorado (CDPHE, 2005), Iowa (IDNR, 2004), and Pennsylvania (PDEP, 2000) only apply DO criteria to the epilimnion of stratified water bodies. Other states have vague references to stratification effects in their DO criteria. North Carolina's regulations state that ambient DO can be lower in lake bottom waters "if caused by natural conditions" (NC DENR, 2004). Some states specify DO concentrations for arbitrary depths in the water column. For protection of warm water aquatic life in Kentucky, DO must be measured at "mid-depth in waters 10 ft or less and at representative depth in other waters". For cold water lakes and reservoirs that support trout, the DO concentration "in waters below the epilimnion shall be kept consistent with natural water quality" (KDW, 2004). Tennessee regulations require that DO "be measured at mid-depth in waters 10 ft or less and at a depth of 5 ft for waters greater than 10 ft in depth" (TDEC, 2004).

The existing water quality standards for Virginia recognize the effects of stratification on hypolimnetic DO concentrations as referenced in Section 9 VAC 25-260-55 (VDEQ, 2004b). However, the State Water Control Board may have difficulty establishing site-specific DO criteria "that reflect the natural quality of that water body or segment", in accordance with Part E, because no natural reference conditions exist for constructed impoundments (refer to additional discussion in Response 4).

Currently, the Virginia Department of Environmental Quality (DEQ) applies existing DO criteria to the entire water column of lakes and reservoirs during stratified and non-stratified conditions (Younos, 2004). This has resulted in a number of impoundments being classified as Category 4 (does not require a TMDL) or 5 (requires a TMDL) impaired because of DO criteria violations (Table 1) (VDEQ, 2004d). Category 4 and 5 waters are those that were determined to be impaired due to natural and anthropogenic sources, respectively. DEQ applied a multi-step procedure to establish whether anthropogenic pollutants were causing hypolimnetic DO violations. The general approach involves assessment of water quality data and evaluation of anecdotal information in the watershed. Trophic State Indices (TSIs) were calculated for each impaired water body to determine if excessive nutrients are contributing to low DO concentrations in the hypolimnion.

The current methodology used by DEQ to apply existing DO criteria to constructed impoundments is sound and scientifically defensible. Until revised DO criteria that more specifically address stratification and designated uses in lakes and reservoirs are established, the current approach should be adequate. After development of revised DO criteria, reservoirs that

were previously classified as Category 5 impaired may be reclassified as waters supporting one or more designated uses. Therefore, effort should be focused on determining reservoir-specific DO criteria before proceeding with TMDL development for Category 5 DO-impaired waters.

2. Should dissolved oxygen criteria be developed specifically for lakes?

The committee recommends that DO criteria be established specifically for lakes and reservoirs. For development of nutrient criteria for Virginia water bodies, the DEQ plans to classify state surface waters by type (estuaries, lakes and reservoirs, and rivers and streams) (VDEQ, 2004c). Additionally, the Academic Advisory Committee recommended that nutrient criteria development be based on water body types (Virginia Water Resources Research Center, 2004). Therefore, it is likely that nutrient criteria will be proposed and referenced by water type. Developing DO criteria specifically for lakes and reservoirs will provide consistency between water quality regulations. Additionally, lakes and reservoirs respond differently to nutrient inputs than estuaries and rivers and streams, which is why guidance documents for state nutrient criteria development were published by water body type (US EPA, 1998). Differing responses among surface water types will likely translate to differing DO characteristics because DO is a secondary response variable to nutrient loading (Virginia Water Resources Research Center, 2004). Typically, the primary source of oxygen into a water body is atmospheric diffusion. Diffusion of oxygen into and within water is relatively slow, so mixing is required for DO to be in equilibrium with the atmosphere. Consequently, small, turbulent streams and rivers are often near saturation with respect to DO throughout their depths. This is in contrast to the distribution of oxygen in density-stratified lakes and impoundments, which varies with depth and is controlled by hydrodynamics, photosynthetic inputs, and losses to chemical and biotic oxidations (Wetzel, 2001).

The committee also recommends that DO criteria development for lakes and reservoirs be based on designated uses of the water bodies. Basing DO criteria on designated uses is similar to the approach used by EPA for development of ambient DO criteria for the Chesapeake Bay and its tidal tributaries (US EPA, 2003). It is also consistent with previous recommendations of the Academic Advisory Committee (Virginia Water Resources Research Center, 2004). Basing water quality criteria on designated uses has been applied successfully by British Columbia for developing phosphorus criteria and is also used by the Canadian Federal government in specifying a number of water quality parameters (US EPA, 2000).

3. If the answer to no. 2 is yes, should dissolved oxygen criteria be developed that apply to the entire water column or to the upper layer only or should there be different criteria for different depths within a lake?

To address the effects of stratification on DO concentrations throughout the water column, the committee recommends that separate criteria be developed for the epilimnion and hypolimnion and that criteria development be based on designated uses of the water bodies. Application of a single DO criterion for all depths within a given lake or reservoir may be unnecessarily stringent and not required to fully support the water body's designated uses during stratification. When the water column is completely mixed, a single DO criterion that supports the waterbody's designated uses should be applied to all depths. If the primary cause of anoxic

conditions in the lower depths of stratified impoundments is lack of reaeration by the atmosphere, then, theoretically, oxic conditions should exist when the lake is completely mixed.

Dissolved oxygen criteria for stratified water bodies should ensure that at least one layer exists in the reservoir where temperature, DO, and pH requirements are being met to support designated uses. A similar approach has been proposed for thermally stratified reservoirs in Oregon, although specific DO criteria for the hypolimnion have not been developed (ODEQ, 2004). As an example, if DO criteria are developed for protection of warm water aquatic life in a particular reservoir, specifying DO criteria for the hypolimnion may not be necessary if water quality conditions in the epilimnion can support the target species throughout the stratification period. With regard to protection of water supply use, hypolimnetic DO criteria may not be required for a given impoundment if water utility(ies) can only withdraw raw water for treatment from the epilimnion.

Specifying different DO criteria for different water column depths or regions has recently been applied by EPA to the Chesapeake Bay and its tidal tributaries (US EPA, 2003). Dissolved oxygen criteria were derived to protect estuarine species living in different habitats, also referred to as tidal water designated uses, which are influenced by natural processes in the Bay. The criteria reflect ambient oxygen dynamics, as evidenced by seasonal application of deep-water and deep-channel DO criteria that account for the effects of water column stratification. Both deep-water and deep-channel regions are below the pycnocline during periods of Bay stratification (late spring to early fall). Deep-water criteria were set at levels to protect shellfish and juvenile and adult fish, and to foster recruitment success of the bay anchovy. Deep-channel criteria were set to provide seasonal refuge and to protect the survival of bottom sediment-dwelling worms and clams. During periods of complete water column mixing, the higher DO criteria associated with open-water fish and shellfish use applies to deep-water and deep-channel designated uses (US EPA, 2003).

4. Should dissolved oxygen criteria be established by lake use (water supply, fishing, or recreation)?

Because the vast majority of lentic systems in Virginia are constructed impoundments, establishing DO criteria based on water body designated use is a reasonable methodology. This approach is a logical step considering reservoirs are artificial water bodies created for specific uses and functions. Impoundments are built and managed for various purposes including flood control, navigation, municipal or agricultural water supply, hydroelectric generation, and game fish production. Management practices often affect physical, biological, and chemical characteristics of the reservoir (US EPA, 2000). Developing DO criteria based on designated impoundment uses is recommended over specifying criteria based on a reference condition approach because the reference or undisturbed state for a reservoir is usually a lotic ecosystem. Therefore, the reference condition method is not at all applicable to constructed impoundments. Basing DO criteria on reservoir uses will avoid unnecessarily stringent criteria being applied to some water bodies while still protecting designated and existing uses. For instance, it is likely that the minimum DO criteria for protection of recreation use or water supply use is lower than that required for protection of aquatic life. For aquatic life use, minimum DO needs can vary depending on the target species (cold water or warm water).

Designated uses have already been determined for Virginia water bodies for biennial preparation of the 305(b)/303(d) integrated water quality assessment. The six existing

designations are aquatic life use, fish consumption use, shellfish consumption use, swimming use, public water supply use, and wildlife use (Virginia DEQ, 2004d). Of these designated uses, only aquatic life and public water supply are directly affected by low DO concentrations in the water column of lakes reservoirs, and recreation may be considered to be indirectly affected. Compliance with fish consumption use is determined by comparison of fish tissue data with state screening values for toxic pollutants. Shellfish consumption use is not impaired if harvesting restrictions are not issued by the Virginia Department of Health. Criteria for support of wildlife use involve toxics known to be harmful to aquatic life in the water column. Currently, support of swimming use for a water body is demonstrated by compliance with bacteriological criteria such as fecal coliform and *E. coli* (Virginia DEQ, 2004).

Ambient freshwater DO criteria for the protection of aquatic life, both cold and warm water species, have been determined previously by EPA (US EPA, 1986). In preparation of DO criteria specific to the Chesapeake Bay, EPA conducted a preliminary survey of the literature since the 1986 freshwater document was published and found effects data that confirmed that the DO criteria remained protective. Therefore, EPA believes that the existing freshwater criteria accurately account for the anticipated effects of low DO on freshwater aquatic species (US EPA, 2003).

To the committee's knowledge, EPA has not developed ambient DO criteria for the support of public water supply use in lakes and reservoirs, and neither have most states. Alaska specifies that DO concentrations must be at least 4 mg L^{-1} in waters designated for drinking water supply. However, this standard does not apply to lakes or reservoirs where water is withdrawn from below the thermocline (ADEC, 2003). Colorado requires minimum DO concentrations of 3 mg L^{-1} for waters designated for domestic water supply, but the standard is intended to apply to only the epilimnion and metalimnion of stratified lakes and reservoirs (CDPHE, 2005). Florida and West Virginia have specified that surface waters used for potable water supply have DO concentrations of at least 5 mg L^{-1} (FDEP, 2002 and WV EQB, 2004).

Hypolimnetic oxygen depletion in stratified water bodies may lead to increases in hydrogen sulfide, ammonia, and phosphorus, and the release of reduced iron and manganese from the sediments. If entrained into the productive surface zone, phosphorus may stimulate algal growth, which exacerbates the problem because decaying algae ultimately fuel additional oxygen demand. Hydrogen sulfide and reduced iron and manganese are undesirable in drinking water and usually require additional treatment (Cooke and Carlson, 1989). The extra oxidant may react with natural organic matter increasing the formation of disinfection by-products.

The effects of hypolimnetic anoxia on chemical and biological parameters of concern to drinking water treatment are well documented. However, a cursory review of the scientific literature revealed little information on suggested DO criteria for protection of raw water supplies. The published studies that are most relevant to the effects of low DO concentrations on water treatment processes involve hypolimnetic aeration or oxygenation. These techniques are commonly used to add dissolved oxygen to water bodies while preserving stratification. Studies documenting the effects of hypolimnetic aeration and oxygenation have been reviewed by Fast and Lorenzen (1976), Pastorok et al. (1982), McQueen and Lean (1986), and Beutel and Horne (1999). McQueen and Lean (1986) found that for generally all installations, hypolimnetic oxygen levels increased; iron, manganese, and hydrogen sulfide levels decreased; and chlorophyll levels were not altered. The effects of hypolimnetic aeration on phosphorus were more variable. McQueen et al. (1986) attribute this to pH levels and iron availability for phosphorus sedimentation. The effects on nitrogen were not consistent either; ammonium and

total nitrogen decreased in some studies but increased in others. In their review, Beutel and Horne (1999) reported that average hypolimnetic DO concentrations were maintained at greater than 4 mg L⁻¹ in all cases and oxygenation decreased hypolimnetic concentrations of dissolved phosphorus, ammonia, manganese, and hydrogen sulfide by 50-100 percent.

A number of hypolimnetic oxygenation systems have been installed in potable water supply lakes or reservoirs. The City of Norfolk installed hypolimnetic aerators in Lakes Prince and Western Branch, Virginia, two water supply reservoirs. Because of the aeration system, the City has discontinued prechlorination of raw water at the treatment plant, and noticeable improvements have been observed in reservoir aesthetics (Cumbie et al., 1994). St. Mary Lake, British Columbia is a multi-use water body that supports potable water supply, a trout fishery, and recreation. An aeration system installed in 1985 has generally maintained DO at 5 mg L⁻¹ in the hypolimnion and has decreased phosphorus concentrations (Nordin et al., 1995). Hypolimnetic oxygenation in Upper San Leandro Reservoir, California decreased ozone requirements by 35 percent and chlorine requirements by 14 percent at the treatment facility. Also, manganese concentrations in the raw water were decreased, resulting in decreased chlorine dosing. Consequently, the concentration of trihalomethanes in the finished water, which are regulated disinfection by-products, decreased by over 50 percent. Overall, the oxidant savings was greater than twice the cost of oxygen required to operate the hypolimnetic oxygenation system (Jung et al., 2003).

To provide some insight into the potential economic impact of remediating low-DO conditions in Virginia reservoirs, capital costs for select aeration and oxygenation systems are shown in Table 2. The primary types of devices currently in use include full-lift aerators, Speece Cones, and bubble plume diffusers. Full-lift aerators operate by injecting compressed air near the bottom of the hypolimnion. The air-water mixture travels up a vertical pipe to the lake surface where gasses are vented to the atmosphere. The aerated water is then returned through another pipe downward to the hypolimnion. In Speece Cones, oxygen is injected into an enclosed chamber that is typically located in the hypolimnion, and water is either pumped or entrained into the device (Beutel and Horne, 1999). Oxygen transfer occurs within the chamber, and oxygenated water is discharged to the hypolimnion. Pure oxygen or compressed air can also be introduced into the hypolimnion through the use of diffusers to form a rising, unconfined bubble plume. This oxygenation method is most suitable for deep lakes where the bulk of the bubbles dissolve in the hypolimnion and the momentum produced by the plume is low enough to prevent intrusion into the thermocline (Wüest et al. 1992).

It should be noted that maintenance of oxic conditions in the hypolimnion does not always result in a reduction of productivity and algal growth in lakes. Based on more than 10 years of data on hypolimnetic oxygenation and artificial mixing in two eutrophic lakes, Gächter and Wehrli (1998) found that internal cycling of phosphorus was not affected by increased hypolimnetic DO concentrations. Their research indicated that the sediment-water interface remained anoxic even in the presence of an oxic hypolimnion. The authors concluded that excessive organic matter loading and phosphorus precipitation exhausted the hypolimnetic DO supply and exceeded the phosphorus retention capacity of the sediments after diagenesis.

In summary, the information currently available regarding appropriate DO criteria for lakes and reservoirs used for drinking water supply is limited to non-existent. EPA has not developed ambient DO criteria for the support of public water supplies, and the vast majority of states do not have DO criteria specifically for this designated use. The effects of hypolimnetic anoxia on water quality parameters related to drinking water treatment are well documented, and

hypolimnetic oxygenation is a proven mitigation technique. However, because of insufficient information available at this time, the committee can recommend only preliminary DO criteria for protection of water supply designated uses. It is suggested that the existing freshwater DO criteria for non-trout waters (5 mg L^{-1} daily average, 4 mg L^{-1} minimum) be applied to all strata used for potable water supply within a given reservoir. This is comparable to the approximate, rule-of-thumb DO value of 5 mg L^{-1} typically desired in influent raw water by treatment plant managers. It should be noted that maintaining DO at this level is commonly thought to decrease soluble iron and manganese concentrations and control the formation of hydrogen sulfide, but this has not been well established. Therefore, DO criteria for protection of water supply designated uses may need to be revised after further study by EPA or the scientific and engineering community.

Regarding primary and secondary contact recreation, the committee is not aware of DO criteria development by EPA for the protection these designated uses. Also, the vast majority of states have not developed DO standards for recreational uses or the aesthetic quality of lakes and reservoirs. Where such state criteria exist, they are typically part of an all-encompassing limit to be applied to the most sensitive designated water use. One exception is Alaska, which specifies that DO concentrations must be at least 4 mg L^{-1} in waters designated for primary or secondary contact recreation (ADEC, 2003). Also, Colorado requires minimum DO concentrations of 3 mg L^{-1} for primary and secondary contact recreational waters. However, the standard is intended to apply to only the epilimnion and metalimnion of stratified lakes and reservoirs (CDPHE, 2005). South Dakota specifies minimum DO levels of 5 mg L^{-1} for immersion recreation and limited contact recreation waters (SDDENR, 1997). In Virginia, if all reservoirs are designated for aquatic life and/or water supply use, the DO criteria to support these uses would more than likely be adequate to support swimming and other recreational uses. Therefore, separate DO criteria specifically for recreation and aesthetics are probably not necessary for Virginia. A similar conclusion was drawn for application of DO standards in waters of British Columbia (BC MELP, 1997).

5. Should dissolved oxygen criteria differ for natural lakes and constructed impoundments?

The committee recommends that separate DO criteria be developed for natural lakes and constructed impoundments. While studies of reservoir ecosystems have found functional similarities between artificial and natural lakes, natural lake ecosystems have many characteristics that are significantly different than reservoirs. The ratio of drainage basin area to water body surface area is frequently higher for reservoirs than natural lakes (Cooke and Carlson, 1989). Because reservoirs are usually formed in river valleys, their morphometry is typically dendritic, narrow, and elongated. This is in contrast to the predominantly circular or elliptical shape of natural lakes (Wetzel, 2001). Most reservoirs have asymmetrical depth distributions in the longitudinal direction, with the maximum depths occurring adjacent to the dam. Near the vertical dam wall, unusual chemical and temperature stratifications can occur, which differ dramatically from those typically present in natural lakes (Cole, 1994). Reservoirs often have higher flushing rates and lower hydraulic residence times than natural lakes. Additionally, discharges from reservoirs are not always from the surface and are frequently from deeper waters. Because reservoirs are constructed for various uses, surface levels in these water bodies typically fluctuate more than in natural lakes as water is stored and released (Cole, 1994).

Because the watershed area in relation to surface area for reservoirs is much larger than for natural lakes, inflows to reservoirs have more energy for erosion, higher sediment-load carrying capabilities, and cause increased dispersion of dissolved and particulate concentrations into the receiving water body. Runoff influent to reservoirs is usually greater and influenced more significantly by precipitation events. These characteristics induce higher but more irregular nutrient and sediment loading rates in reservoirs compared to natural lakes, which affects biological processes (Wetzel, 2001). In turn, differences in light attenuation and nutrient availability between natural and artificial lakes can result in different productivity rates and, subsequently, differing hypolimnetic dissolved oxygen concentrations. Dissolved oxygen is a secondary response variable to nutrient inputs (Virginia Water Resources Research Center, 2004).

The committee recommends that site-specific dissolved oxygen criteria be developed for the two natural lakes in the state, Mountain Lake and Lake Drummond. These water bodies are located in distinctly different ecological regions, and hence, each is a unique natural resource. Mountain Lake is the only notable natural lake in the unglaciated region of the southern Appalachian Highlands (Cawley et al., 2001). Lake Drummond is a blackwater lake located in the Great Dismal Swamp, which is considered to be the most northern “southern” type swamp on the east coast of the United States (Johannesson et al., 2004). In addition to dissolved oxygen data currently collected on Lake Drummond by the Virginia Department of Environmental Quality (Younos, 2004), numerous studies have been published on Mountain Lake (Simmons and Neff, 1974; Obeng-Asamoah, 1976; Parson, 1988; Beaty and Parker, 1993; Beaty and Parker, 1995; Cawley et al., 1999) and Lake Drummond (Duke et al., 1969; Anderson et al., 1977; Phillips and Marshall, 1993; Merten and Weiland, 2000). This information can facilitate development of site-specific dissolved oxygen criteria for each natural water body.

These recommendations are consistent with related recommendations of the Academic Advisory Committee regarding freshwater nutrient criteria (Virginia Water Resources Research Center, 2004).

6. Should dissolved oxygen criteria be developed specifically for the hypolimnion?

Expanding on the response to question 3, the committee believes that dissolved oxygen criteria should be developed specifically for the hypolimnion of constructed impoundments to address the effects of stratification. As stated previously, hypolimnetic DO criteria should take into account designated uses of the water body and what conditions will be required in the hypolimnion to achieve these uses during stratification. This is consistent with the recommendations of the Academic Advisory Committee regarding development of Virginia freshwater nutrient criteria (Virginia Water Resources Research Center, 2004). Additionally, hypolimnetic DO criteria should also consider the potential downstream effects of reduced oxygen concentrations in waters released from the lower depths of constructed impoundments. Per 9 VAC 25-260-10 of the Virginia Water Quality Standards, “in designating uses of a water body and the appropriate criteria for those uses, the board...shall ensure that its water quality standards provide for the attainment and maintenance of the water quality standards of downstream waters”. Virginia streams and rivers downstream of reservoirs are currently affected by releases of hypolimnetic waters. For example, almost 6 miles of the Roanoke River have been classified as Category 5 impaired waters for DO because of hypolimnetic water discharge upstream from Lake Gaston (VDEQ, 2004d). Also, nearly 6 miles of the Meherrin

River are designated Category 5 impaired for DO due to hypolimnetic releases from an upstream impoundment (VDEQ, 2004d).

The release of hypoxic or anoxic waters from stratified impoundments is currently regulated for licensure of existing and new hydropower projects. The United States Federal Energy Regulatory Commission (FERC) is increasingly specifying minimum DO concentrations in discharge waters from hydropower reservoirs (Mobley, 1997).

7. What type of Use Attainability Analysis (UAA) would be needed to demonstrate appropriate dissolved oxygen criteria for lakes?

In order to demonstrate appropriate DO criteria for lakes and reservoirs, a multi-phase Use Attainability Analysis (UAA) is recommended. In accordance with applicable UAA methodology (US EPA 1994; OWR 2001; VDEQ 2004a), the committee feels that a comprehensive multi-phase UAA approach should be based on:

1. A review of supporting literature and historical data
2. Routine, on-site surveys performed to analyze parameters relating to DO levels (e.g., sediment loading and organic matter (OM) deposition rates, nutrient loading (especially phosphorous (P)), hydraulic input and withdrawal locations within a limnological system, stratification depths, and specific chemical analyses such as DO (via Hydrolab and modified Winkler measurements), total-P (TP), BOD, and COD)
3. Correlation of TP TSI approach with epilimnetic and hypolimnetic DO measurements to help establish overall UAA (see further discussion in Response 9)

A multi-phase UAA approach would best characterize the combined influence of the various processes impacting DO levels (in both the epilimnion and the hypolimnion) and subsequent attainable use on a site-specific basis. Epilimnetic oxygen levels are primarily controlled by photosynthesis, microbial respiration, resupply from the atmosphere, and water column demand. Hypolimnetic oxygen levels are typically governed by sediment oxygen demand (SOD). Organic or nutrient loading of thermally stratified lakes and reservoirs may lead to significant depletion of DO in the lower hypolimnetic water. Hypolimnetic oxygen depletion often results in the release of Fe, Mn, and P from sediment oxide precipitates, thereby decreasing water quality and increasing drinking-water treatment costs. Release of P can promote excessive algal growth, which stimulates eutrophication and can have detrimental effects on the health and diversity of the plant, fish, and benthic populations. The abundance of algae is directly influenced by the ratios of supplied nutrients. Even small differences in the nutrient ratios (e.g., N to P) can have significant effects on competing algal species (Gächter and Muller 2003; Lewandowski et al. 2003). Additional oxygen is consumed as these algal blooms die, settle into the hypolimnion, and are degraded by aerobic sediment microbes. Sediment loading may also impact oxygen demand by introducing additional Fe, Mn, and P into the system and by partially controlling oxygen diffusion rates into the sediment (Muller et al. 2002). Thus, when evaluating use attainability, it is important to consider all influences on DO levels: water column demand, respiratory demand via microorganisms, SOD, and oxygen resupply. Optimal water quality and corresponding use may be established and maintained by controlling P loading or by adding oxygen to lake and reservoir systems. Hypolimnetic oxygenation systems, which preserve stratification, are increasingly used to replenish DO (refer to Response 4).

Due to the fact that complex interactions between oxygen availability and P cycling have such control on water quality and subsequent use attainability, the committee recommends using

DO and TP as key parameters in use attainability analyses. It has been shown that DO levels may not directly correlate with soluble P levels due to benthic microbial activity and the formation of ferrous (reduced Fe) phosphate precipitates, thus supporting the need to separately quantify both DO and TP levels (Gächter and Muller 2003). Because of the various nutrient and oxygen requirements specific to each designated use (e.g., cold-water fishery vs. drinking water supply), it seems that a UAA evaluating both DO and TP levels should be performed to address the particular attainable use criteria for a site.

8. Can historical DO/temperature depth profile data such as the 1983 EPA Clean Lakes Program funded 8 month sampling of 32 lakes in VA be used to demonstrate expected dissolved oxygen levels in undisturbed or forested watersheds?

Historical DO and temperature depth profile data may be extremely valuable resources for establishing DO reference levels and anticipated stratified zones. Historical data, such as that obtained during the 1983 EPA Clean Lakes VA sampling program, can be used to establish *expected*, base-line DO levels for watersheds with conditions similar to those sampled during this EPA study. However, this data should be used predominantly for general guideline purposes, as information obtained during the 1983 EPA Clean Lakes study was collected primarily to establish base-line data in preparation for subsequent Clean Lakes Program projects (US EPA 1982). Base-line DO estimates should be verified by current DO measurements and modified in order to accurately characterize existing, reservoir-specific conditions. DO availability and depletion rates are very site-specific and transient as they may be significantly influenced by variables including sedimentation rates, nutrient loading, OM deposition, local sediment mineral (e.g., Fe, Mn, Ca, P) composition, and lake morphometry. Unfortunately, inadequate tributary data were obtained during the EPA sampling program due to drought conditions at the time of testing (US EPA 1982). Thus, the transient and possibly considerable influence of nutrient and sediment loading was not included in the subsequent trophic state evaluations.

The concentration and decay of OM present at the sediment surface are typically considered to govern oxygen demand (particularly hypolimnetic) in lakes and reservoirs, with high concentrations of OM resulting in an increased oxygen demand (Kalin and Hantush 2003). However, evidence shows that organic degradation rates may not directly correlate with OM concentrations, raising the possibility that different levels of oxygen availability and differing rates of OM delivery via sediment focusing may govern SOD (Meckler et al. 2004). Thus, variations in oxygen availability, nutrient loading, and OM concentrations (all of which are highly site-specific parameters) may have significant impact on nutrient cycling, SOD, and hypolimnetic DO levels on a reservoir-specific basis.

In addition to establishing base-line DO estimates, historical data may also be very useful for determining trends in DO and temperature over time as a function of variations in anthropogenic and natural influences (Evans et al. 1996; Nishri et al. 1998; Little and Smol 2001). It is likely that these influences have changed significantly since the early 1980's in many VA regions, resulting in altered DO and temperature conditions from those documented during the 1983 EPA Clean Lakes VA sampling program. Research has shown that temporal and spatial variations in lacustrine processes may have considerable control over subsequent SOD, DO, and TP levels (Hanson et al. 2003; House 2003; Kalin and Hantush 2003; Dittrich et al. 2004; Meckler et al. 2004). Transient lacustrine processes (e.g., sediment loading following storm events and intermittent accumulation of OM) can have a substantial impact on SOD in the

zone-of-influence downstream of the discharge point in many systems, subsequently impacting water-column DO levels. Nishri et al. (1998) found significant variations in limnological parameters over time with epilimnetic DO concentrations increasing by ~ 20%, hypolimnetic H₂S concentrations increasing ~ 75%, and a long-term decrease in zooplankton biomass (~ 50%) from 1970 to 1991 as a result of reduced allochthonous OM loading and enhanced OM burial in the hypolimnetic sediments of Lake Kinneret (Israel). Significant variations in sediment loading and OM deposition may have occurred in numerous VA lakes and reservoirs during the last two decades. Because OM deposition and accumulation over time have been shown to have strong influence on sediment composition and trends in lake metabolism and DO levels, existing conditions may deviate considerably from DO and temperature data obtained during the 1983 EPA study (Hanson et al. 2003).

Each reservoir is impacted differently by both external (e.g., anthropogenic nutrient loading, hydraulic inputs (river, streams), local soil/mineral composition, allochthonous OM loading) and internal (bank erosion, water-withdrawal locations, autochthonous OM loading, lake morphometry) processes that have strong influence on DO levels. Using historical data from 32 of the 100+ constructed reservoirs in VA for current estimates of existing reservoir DO in undisturbed regions may therefore inadequately represent specific reservoir conditions. Nevertheless, historical DO and temperature profiles can be invaluable for establishing background information and general estimates of DO levels in undisturbed, forested areas, especially when paired with current DO measurements and site-specific data.

9. Could the TMDL program TP/DO TSI approach be used as a template for UAA demonstrations?

The Trophic State Index (TSI) total phosphorus (TP) approach is established as a predictor of algal biomass as a function of soluble TP (Carlson 1977). A TSI value of 60 or greater for any one of the 3 indices (chlorophyll-a (CA), Secchi disk (SD), and TP) indicates that nutrient loading is negatively impacting designated uses of a particular lake or reservoir. A TSI value of 60 corresponds to a CA concentration of 20 ug/l, a SD measurement of 1 meter, and a TP concentration of 48 ug/l. TSI ratings are based on the following equations, as defined by (Carlson 1977):

$$TSI(SD) = 10(6 - (\ln SD / \ln 2))$$

$$TSI(CA) = 10(6 - ((2.04 - 0.68 \ln CA) / (\ln 2)))$$

$$TSI(TP) = 10(6 - ((\ln 48 / TP) / (\ln 2)))$$

TP is a significant parameter for characterizing limnological trophic states and the TP TSI approach may yield a satisfactory approximation of oxygen availability/depletion with respect to certain attainable use determinations. However, while strongly indicative of potential eutrophication problems, TP analyses alone may not comprehensively indicate corresponding DO levels. Admittedly, this may or may not be problematic depending on the intended use of the lake or reservoir of concern.

Because of the complex interactions between oxygen levels and P cycling (as defined in Response 7) and the resulting impacts on water quality, it is important to evaluate both P and DO levels when estimating potential DO demand and subsequently establishing DO criteria. A combined TP/DO TSI approach may be an appropriate method for establishing UAA

demonstrations as long as both TP and DO levels are quantified and correlated. While TP can be a strong indicator of DO levels and trophic states, particularly in regions of high photosynthetic activity and productivity, other biogeochemical processes may strongly impact DO in hypolimnetic regions. Conventional wisdom suggests that oxic sediments retain Fe, Mn, and P, thereby promoting improved water quality, while anoxic conditions exacerbate water quality as these chemicals and associated compounds are released into the hypolimnion. However, recent studies have suggested that benthic microbial activity and the formation of ferrous phosphate precipitates (e.g., vivianite) may have a significant influence on sediment/water cycling of chemicals and biomineral formation (Gächter and Muller 2003), indicating that the conventional wisdom needs to be re-examined. Thus, elevated hypolimnetic DO concentrations may not necessarily result in increased P retention in the benthic sediments or reduced TP levels from the water column. Conversely, low TP concentrations in the water column may not always be indicative of relatively high levels of hypolimnetic DO, as it is possible that considerable P remains complexed in ferrous precipitates under low DO conditions.

Thus, depending on water use, TSI TP data alone may or may not be directly representative of water quality and corresponding DO criteria (Carlson 1977). It seems that it would be highly beneficial to pair TP TSI data with supporting DO measurements. A strong UAA approach could be established by incorporating TP TSI methodology with routine DO measurements (particularly during stratification) and site-specific data to determine potential drains on oxygen demand via natural (sediment deposition, introduced Fe- and Mn-minerals, retention time) and anthropogenic (nutrient loading, hydraulic inputs and withdrawals) sources. This approach would use soluble TP and DO measurements to identify potential eutrophication problems that may exacerbate DO depletion and subsequently decrease water quality.

Conclusions and Recommendations

In summary, the committee recommends that DO criteria be established specifically for Virginia lakes and reservoirs and that separate criteria be developed for natural lakes and constructed impoundments. Site-specific criteria should be developed for the two natural lakes in the state, Mountain Lake and Lake Drummond. To address the effects of stratification on DO concentrations throughout the water column, separate criteria for the epilimnion and hypolimnion are recommended, and criteria development should be based on designated uses of the water bodies. Application of a single DO criterion for all depths within a given lake or reservoir may be unnecessarily stringent and not required to fully support the water body's designated uses during stratification. Dissolved oxygen criteria for stratified water bodies should ensure that at least one layer exists where temperature, DO, and pH conditions can support designated uses.

Hypolimnetic DO criteria should account for the potential downstream effects of reduced oxygen concentrations in waters released from the lower depths of constructed impoundments. Currently, almost 6 miles of the Roanoke River are classified as Category 5 impaired waters for DO because of hypolimnetic water discharge upstream from Lake Gaston (VDEQ, 2004d). Also, nearly 6 miles of the Meherrin River are designated Category 5 impaired for DO due to hypolimnetic releases from an upstream impoundment (VDEQ, 2004d).

Because the vast majority of lentic systems in Virginia are constructed impoundments, establishing DO criteria based on water body designated use is a reasonable methodology. Designated uses have already been determined for Virginia water bodies for biennial preparation

of the 305(b)/303(d) water quality assessment reports (VDEQ, 2004d). Of the six existing designated uses, only aquatic life and public water supply are directly affected by low DO concentrations in lakes reservoirs, and recreation may be considered to be indirectly affected. Ambient freshwater DO criteria for the protection of aquatic life, both cold and warm water species, have been determined previously by EPA (US EPA, 1986).

EPA has not developed ambient DO criteria for the support of public water supplies, and the vast majority of states do not have DO criteria specifically for this designated use. The effects of hypolimnetic anoxia on water quality parameters related to drinking water treatment are well documented. However, because of insufficient information available, the committee can recommend only preliminary DO criteria for protection of water supply uses. It is suggested that the existing freshwater DO criteria for non-trout waters (5 mg L^{-1} daily average, 4 mg L^{-1} minimum) be applied to all strata used for potable water supply within a given reservoir. This is comparable to the approximate, rule-of-thumb DO value of 5 mg L^{-1} typically desired in influent raw water by treatment plant managers. Because the direct treatment benefits of this particular DO concentration in lakes and reservoirs have not been well established, DO criteria for protection of water supply designated uses may need to be revised after further study by EPA or the scientific and engineering community.

Separate DO criteria specifically for protection of recreational uses is not recommended at this time for Virginia. If all reservoirs are designated for aquatic life and/or water supply use, then the DO criteria to support these uses would more than likely be adequate to support primary and secondary recreational uses.

Compliance with DO criteria in lakes and reservoirs will likely be determined through field data collection. Measurements are typically obtained at appropriate intervals through the water column on each sampling date. Dissolved oxygen concentrations are measured with a sensing probe or using a modified Winkler technique. The minimum frequency for characterizing mixing and the oxic status of a water body is dependent on the oxygen depletion rate. In some locations, the minimum required frequency may be monthly; in others, it may be as high as daily (US EPA, 2000). Temperature profiles will also be required to determine the onset of stratification and to delineate the density strata within water bodies. Dissolved oxygen data from most, if not all, of Virginia's significant reservoirs has been or is currently being collected, as evidenced by the biennial 305(b)/303(d) water quality assessment reports (VDEQ, 2004d). To ensure that representative DO data are being obtained to accurately characterize each reservoir's oxic status, existing sampling procedures should be reviewed. As referenced in the Nutrient Criteria Technical Guidance Manual—Lakes and Reservoirs (US EPA, 2000), there are a number of publications that provide further information on sampling designs for lakes and reservoirs (Carlson and Simpson, 1996; Gaugush, 1987; Gaugush, 1986; Reckhow, 1979; Reckhow and Chapra, 1983).

With respect to the type of Use Attainability Analysis (UAA) needed to demonstrate appropriate DO criteria for lakes and reservoirs, a multi-phase UAA is recommended, based on 1) a review of supporting literature and historical data; 2) routine, on-site surveys performed to analyze parameters relating to DO levels; and 3) correlation of TP TSI approach with epilimnetic and hypolimnetic DO measurements to help establish overall UAA. The committee feels that a multi-phase UAA approach would best characterize the combined influence of the various processes impacting DO levels (in both the epilimnion and the hypolimnion) and subsequent attainable use on a site-specific basis. Due to the fact that complex interactions between oxygen

availability and P cycling have such control on water quality and subsequent use attainability, the committee recommends using DO and TP as key parameters in use attainability analyses.

Historical data, such as that obtained during the 1983 EPA Clean Lakes VA sampling program, may be very useful for establishing *expected*, base-line DO levels for watersheds with conditions similar to those sampled during the 1983 sampling program. Additionally, historical data may also be valuable for determining trends in DO and temperature over time as a function of variations in anthropogenic and natural influences. Regarding the use of historical data for estimates of current DO conditions, this data should be used predominantly for general guideline purposes, as information obtained during the 1983 EPA Clean Lakes study was collected primarily to establish base-line data in preparation for subsequent Clean Lakes Program projects (US EPA 1982). Base-line DO estimates should be verified by current DO measurements and modified with respect to existing, reservoir-specific conditions. DO availability and depletion rates are very site-specific and transient as they may be significantly influenced by variables including sedimentation rates, nutrient loading, OM deposition, local sediment mineral (e.g., Fe, Mn, Ca, P) composition, and lake morphometry. Thus, variations in oxygen availability, nutrient loading, and OM concentrations (all of which are highly site-specific parameters) may have significant impact on nutrient cycling, SOD, and hypolimnetic DO levels, emphasizing the need for current DO measurements on a reservoir-specific basis.

The committee feels that a combined TP/DO TSI approach may be an appropriate method for establishing UAA demonstrations as long as both TP and DO levels are quantified and correlated. Because of the complex interactions between oxygen levels and P cycling and the resulting impacts on water quality, it is important to evaluate both P and DO levels when estimating potential DO demand and subsequently establishing DO criteria. While TP may be a strong indicator of DO levels and trophic states, particularly in regions of high photosynthetic activity and productivity, other biogeochemical processes may strongly impact DO in hypolimnetic regions. A strong UAA approach could be established by incorporating TP TSI methodology with routine DO measurements and site-specific data to determine potential drains on oxygen demand via natural and anthropogenic sources. This approach would use soluble TP and DO measurements to identify potential eutrophication problems that may exacerbate DO depletion and subsequently decrease water quality.

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Table 1. Significant Reservoirs by Region as of August 2004 (VDEQ, 2004d)

Reservoir	Location	Surface Area (acres)	Public Water Supply?	2004 DO Impairment Category
Northern Regional Office – 13 Lakes				
Able Lake	Stafford County	185	Yes	
Lake Anna	Louisa County	9,600		
Aquia Reservoir (Smith Lake)	Stafford County	219	Yes	
Beaverdam Reservoir	Loudoun County	350	Yes	
Burke Lake	Fairfax County, VDGIF	218		
Goose Creek Reservoir	Loudoun County	140	Yes	
Lake Manassas	Prince William County	741	Yes	
Motts Run Reservoir	Spotsylvania County	160	Yes	
Mountain Run Lake	Culpepper County	75	Yes	5C
Ni Reservoir	Spotsylvania County	400	Yes	
Northeast Creek Reservoir	Louisa County	49	Yes	
Ocoquan Reservoir	Fairfax County	1,700	Yes	5C
Pelham Lake	Culpepper County	253	Yes	5C
Piedmont Regional Office – 11 Lakes				
Airfield Pond	Sussex County, VDGIF	105		
Amelia Lake	Amelia County, VDGIF	110		
Brunswick Lake	Brunswick County, VDGIF	150		
Lake Chesdin	Chesterfield County	3,196	Yes	5A
Chickahominy Lake	Charles City County	1,500	Yes	5A
Diascund Reservoir	New Kent County	1,700	Yes	4C
Emporia Lake	Greensville County	210	Yes	4C
Falling Creek Reservoir	Chesterfield County	110		
Great Creek Reservoir (Bannister Lake)	Lawrenceville	305		4C
Swift Creek Lake	Chesterfield County	156		
Swift Creek Reservoir	Chesterfield County	1,800	Yes	4C
South Central Regional Office – 22 Lakes				
Briery Creek Lake	Prince Edward County, VDGIF	850		
Brookneal Reservoir	Campbell County	25	Yes	
Cherrystone Lake	Pittsylvania County	105	Yes	4C
Georges Creek Reservoir	Pittsylvania County	1	Yes	
Gordon Lake	Mecklenburg County, VDGIF	157		

Reservoir	Location	Surface Area (acres)	Public Water Supply?	2004 DO Impairment Category
Graham Creek Reservoir	Amherst County	50	Yes	4C
Halifax Reservoir	Halifax County	410	Yes	
Holiday Lake	Appomattox County	145		
Kerr Reservoir (VA portion)	Halifax County, VDGIF	35,251	Yes	5A
Keysville Lake	Charlotte County	42	Yes	
Lake Conner	Halifax County, VDGIF	111		
Lake Gaston (VA portion)	Brunswick County	5,529	Yes	5A
Lunenberg Beach Lake	Town of Victoria	13	Yes	
Modest Creek Reservoir	Town of Victoria	29	Yes	
Nottoway Falls Lake	Lunenburg County	60	Yes	5A
Nottoway Lake	Nottoway County	188		
Nottoway Pond	Nottoway County	65	Yes	
Pedlar Lake	Amherst County	75	Yes	5C
Roaring Creek	Pittsylvania County	19	Yes	
Stonehouse Creek Reservoir	Amherst County	125		
Thrashers Creek Reservoir	Amherst County	110		
Troublesome Creek Reservoir (SCS Impoundment No. 2)	Buckingham County	85	Yes	
South West Regional Office – 9 Lakes				
Appalachia Reservoir	Wise County	17	Yes	
Big Cherry Lake	Wise County	76	Yes	5A
Byllsby Reservoir	Carroll County	335		
J. W. Flannigan Reservoir	Dickenson County, ACOE	1,143	Yes	5A
Hungry Mother Lake	Smyth County	108	Yes	5A
Lake Keokee	Lee County, VDGIF	100		5A
Laurel Bed Lake	Russell County, VDGIF	300		
North Fork Pound Reservoir	Wise County, ACOE	154	Yes	5A
South Holston Reservoir	Washington County, TVA	7,580	Yes	5A
Tidewater Regional Office – 20 Lakes				
Lake Cahoon	Suffolk City	508	Yes	
Lake Burnt Mills	Isle of Wight County	711	Yes	
Harwood Mill Pond	York County	300	Yes	5A

Reservoir	Location	Surface Area (acres)	Public Water Supply?	2004 DO Impairment Category
Lake Kilby	Suffolk City	226	Yes	
Lee Hall Reservoir	Newport News	230	Yes	5A
Little Creek Reservoir	Norfolk City	193	Yes	
Little Creek Reservoir	James City County	860	Yes	
Lake Lawson	Norfolk City	77	Yes	
Lone Star Lake F	Suffolk City	20	Yes	
Lone Star Lake G	Suffolk City	50	Yes	
Lone Star Lake I	Suffolk City	39	Yes	
Lake Meade	Suffolk City	511	Yes	
Lake Prince	Suffolk City	946	Yes	
Lake Smith	Norfolk City	193	Yes	5A
Speights Run Lake	Suffolk City	94	Yes	
Stumpy Lake	Virginia Beach	210	Yes	
Waller Mill Reservoir	York County	315	Yes	
Lake Whitehurst	Norfolk City	480	Yes	
Lake Wright	Norfolk City	49	Yes	
Western Branch Reservoir	Norfolk City	1,265	Yes	
Valley Regional Office – 12 Lakes				
Beaver Creek Reservoir	Albemarle County	104	Yes	
Mount Jackson Reservoir	Shenandoah County	0.7	Yes	
Coles Run Reservoir	Augusta County, USFS	9	Yes	
Elkhorn Lake	Augusta County, USFS	55	Yes	4C
Lake Frederick	Frederick County, VDGIF	120		4C
Ragged Mountain Reservoir	Albemarle County	54	Yes	4C
Rivanna Reservoir	Albemarle County	390	Yes	
Staunton Dam Lake	Augusta County	30	Yes	
Strasburg Reservoir	Shenandoah County	5.3	Yes	
Switzer Lake	Rockingham County, USFS	110		
Sugar Hollow Reservoir	Albemarle County	47	Yes	4C
Totier Creek Reservoir	Albemarle County	66	Yes	5A
West Central Regional Office – 15 Lakes				
Beaverdam Creek Reservoir	Bedford County	123	Yes	
Bedford Reservoir	Bedford County	28	Yes	
Carvins Cove Reservoir	Botetourt County	630	Yes	4C
Claytor Lake	Pulaski County	4,483	Yes	4C

Reservoir	Location	Surface Area (acres)	Public Water Supply?	2004 DO Impairment Category
Clifton Forge Reservoir	Alleghany County, USFS	16	Yes	
Fairystone Lake	Henry County	168		
Gatewood Reservoir	Pulaski County	162		
Hogan Lake	Pulaski County	40	Yes	
Leesville Reservoir	Bedford County	3,400	Yes	4C
Little River Reservoir	Montgomery County	113		
Martinsville Reservoir	Henry County	220	Yes	
Lake Moomaw	Bath County, USFS	2,430		4C
Philpott Reservoir	Franklin, Henry, and Patrick Counties; ACOE	2,879		4C
Smith Mountain Lake	Bedford, Franklin, and Pittsylvania Counties	19,992	Yes	4C, 5A
Talbott Reservoir	Patrick County	165		
Total 102 Lakes Statewide				

Table 2. Capital costs of representative hypolimnetic aeration and oxygenation systems.

Waterbody	Maximum Depth (m)	Volume (10^6 m^3)	Aerator or Oxygenator Type	Application	Year Installed	Oxygen Addition (kg d^{-1})	Capital Cost (2005 \$)	References
Richard B. Russell Reservoir, Georgia	47	1,270	bubble plume diffuser	hydropower	1985	200,000	\$1.6M	Mauldin et al. (1988), Beutel and Horne (1999), Little (2005)
Lakes Prince and Western Branch, Virginia	11	38	full-lift aerator	water supply	1991	10.7	\$2.8M	Burris and Little (1998), Burris et al. (2002), Little (2005)
Camanche Reservoir, California	41	545	Speece Cone	hydropower	1993	9,000	\$1.8M	Jung et al. (1999), Little (2005)
Spring Hollow Reservoir, Virginia	55	7.2	bubble plume diffuser	water supply	1998	250	\$120K	Little and McGinnis (2000), Little (2005)
Upper San Leandro Reservoir, California		51	bubble plume diffuser	water supply	2002	9,000	\$450K	EBMUD (2001), Jung et al. (2003), Little (2005)